

**NASA Technical Memorandum 86265**

**Galactic Heavy-Ion Shielding  
Using Electrostatic Fields**

**Lawrence W. Townsend**

**SEPTEMBER 1984**

**NASA**



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# Galactic Heavy-Ion Shielding Using Electrostatic Fields

Lawrence W. Townsend  
*Langley Research Center*  
*Hampton, Virginia*



National Aeronautics  
and Space Administration

Scientific and Technical  
Information Branch

1984



## Introduction

During the period of the 1960's and into the early 1970's, numerous investigations (refs. 1 to 13) were conducted concerning the feasibility of using active radiation shielding methods, such as afforded by electromagnetic fields, as alternatives to the conventional practice of utilizing massive quantities of bulk matter to attenuate space radiations. These active shielding concepts fell into four distinct categories: (1) electrostatic fields; (2) plasma shields; (3) confined magnetic fields; and (4) unconfined magnetic fields. In all these investigations (refs. 1 to 13), consideration was given to shielding against protons or electrons, or both. Shielding against galactic heavy ions was either not considered, or was dismissed as a problem because of their relatively low fluence levels. Recently, there has been some renewed interest in active shielding methods (refs. 14 to 16). The design of reference 14 used an unconfined magnetic field to shield against *all* charged particles up to 15 GeV. Shielding against charged particles with up to 10 GeV of kinetic energy using either electrostatic fields or unconfined magnetic fields was considered in reference 15. The only study in which shielding for a specific galactic heavy ion of interest was investigated was that of reference 16, which considered shielding against 1-GeV/nucleon  $^{56}\text{Fe}$  ions using confined-magnetic-field configurations.

Previous electrostatic shielding studies were limited to consideration of protons from solar flares and the inner Van Allen belt, along with electrons from the solar wind and/or Van Allen belts (refs. 1, 2, 4, 6, and 15). Felten (ref. 3) considered only interplanetary protons and electrons (ignored the radiation belts). A detailed analysis by the Soviets considered only Van Allen belt electrons (ref. 8). Although several of the studies were favorable toward the use of electrostatic shields (refs. 6, 8, and 15), most were not (refs. 1 to 4). The major shortcomings from the latter included: (1) extremely high voltages required; (2) vacuum and insulation breakdown characteristics, which limit minimum structural dimensions; (3) inherent instability of concentric sphere arrangement, which is required for shielding against particles of opposite charge; and (4) production of bremsstrahlung radiation by deflected charged particles.

In this work, attention is specifically focused on using electrostatic fields to shield spacecraft from the galactic heavy ions of major radiobiological interest. In particular, pertinent shield physical parameters are derived and conclusions about electrostatic shielding feasibility are drawn from them. The symbols used in this paper are defined in a list after the references.

## HZE Particles

Primary cosmic-ray particles with a charge number  $Z$  greater than 2 and kinetic energies that can penetrate at least 1 mm of spacecraft or spacesuit shielding (a minimum energy of 10-35 MeV/nucleon depending upon the ion) are usually considered to be HZE particles (ref. 17). The abbreviation "HZE" denotes "high- $Z$  and -energy." Typical fluxes of galactic HZE particles are  $\approx 0.05$  nuclei/cm<sup>2</sup>-sec (ref. 18). HZE particles are known to produce unique biological events called microlesions. Todd (ref. 18) defines a microlesion as a region of focal cellular destruction where there is a core of dead cells surrounded by a penumbra of nonlethally damaged cells. The typical core length is greater than 10 cell diameters with a penumbral radius of about 10  $\mu\text{m}$ . In the penumbra, the delta-ray doses range from 25 to several hundred rads. Reference 18 is an overview of the known biological effects of these microlesions.

The lowest  $Z$ -particles which produce microlesions of the type described here are  $^{20}\text{Ne}$  ions (ref. 18). When weighted over their track length, however, the dominant HZE particles of radiobiological interest are  $^{56}\text{Fe}$  ions. They comprise over 50 percent of the weighted relative abundance of ions heavier than carbon (ref. 17). Todd (ref. 18) estimates that about 27 000 microlesions per cm<sup>3</sup> of tissue would occur for 90 days in geostationary orbit. Most of these, if not all, would be due to  $^{56}\text{Fe}$  nuclei. Since it is known that high-LET (linear energy transfer) particles, such as  $^{56}\text{Fe}$ , are highly carcinogenic, especially for chronic low exposures (ref. 19), and exhibit residual damage effects in skin many years after exposure (ref. 20), the shield analyses in this work focus on these  $^{56}\text{Fe}$  ions of interest.

In the vicinity of the Earth, the flux of Fe nuclei (ref. 17), is approximately 55 per cm<sup>2</sup> per day for energies between 100 MeV/nucleon and 1 GeV/nucleon. For energies above 1 GeV/nucleon, the flux is  $\approx 33$  nuclei per cm<sup>2</sup> per day. Using an assumed energy dependence of the particle flux of (ref. 21)

$$n(> E_c) \propto E_c^{-1.5} \quad (1)$$

yields an Fe flux of 20 nuclei per cm<sup>2</sup> per day for  $E_c > 1.4$  GeV/nucleon and a flux of 12 nuclei per cm<sup>2</sup> per day for  $E_c > 2$  GeV/nuclei. For purposes of analysis, the energy cutoff  $E_c$  at 1.4 GeV/nucleon, which yields a flux of 20 nuclei per cm<sup>2</sup> per day, was arbitrarily chosen. No attempt to correlate this flux to a biological dose will be attempted since the usual concepts of absorbed dose, RBE, and Quality Factor are almost impossible to use for assessing biological hazards due to HZE particles (ref. 18).

## Concentric-Spheres Shielding Analysis

Since HZE particles are positively charged, electro-

static repulsion dictates that the electric-field intensity vector  $\vec{E}$  must point outward away from the shielded volume. The simplest shield configuration would be to cover the spacecraft with a layer of positive charge at a potential large enough to repel all HZE particles with energies up to the desired cutoff. This situation is depicted in figure 1, where for simplicity, a spherical spacecraft of radius  $a$  is assumed. For a  $^{56}\text{Fe}$  nucleus with a cutoff energy of 1.4 GeV/nucleon, the total kinetic energy  $T$  is 78.4 GeV. Since the iron nucleus possesses a charge of  $+26e$  ( $e$  is the unit of electric charge), the required repulsive potential at  $r = a$ , given by

$$V(a) = \frac{T}{Ze} \quad (2)$$

is 3.02 GV. This voltage is approximately 2 orders of magnitude larger than the current state of the art in electrostatic voltage generation. Present tandem Van De Graaff accelerator voltages are less than 30 MV (ref. 22). Even if a potential of 3 GV were attainable, a single spherical shell arrangement containing positive charge would accelerate nearby space electrons to energies  $\approx 3$  GeV. These relativistic electrons, upon striking the spacecraft structure, would generate bremsstrahlung radiation fields inside the spacecraft which would be lethal to the astronauts (ref. 3).

Shielding against radiations of both types (positively charged and negatively charged) requires concentric spherical shells as shown in figure 2. From elementary electromagnetism, the potential can be written in terms of the charges as

$$V(r) = \begin{cases} \frac{Q_a}{4\pi\epsilon_o a} + \frac{Q_b}{4\pi\epsilon_o b} & (r \leq a) \\ \frac{Q_a}{4\pi\epsilon_o r} + \frac{Q_b}{4\pi\epsilon_o b} & (a < r < b) \\ \frac{Q_a + Q_b}{4\pi\epsilon_o r} & (r \geq b) \end{cases} \quad (3)$$

Denoting the potential at  $r = a$  as  $V_a$  and at  $r = b$  as  $V_b$  enables equations (3) to (5) to be written equivalently as

$$V(r) = \begin{cases} V_a & (r \leq a) \\ \frac{bV_b - aV_a}{b - a} - \left(\frac{ab}{b - a}\right) \left(\frac{V_b - V_a}{r}\right) & (a < r < b) \\ \frac{b}{r} V_b & (r \geq b) \end{cases} \quad (6)$$

### Equally and Oppositely Charged Spheres

Since  $Q_a$  and  $Q_b$  must have opposite polarity (to repel oppositely charged particles), one possible config-

uration is  $Q_a = -Q_b$ . In this case,

$$V(r) = \begin{cases} V_a & (r \leq a) \\ \frac{aV_a}{r} \left(\frac{b - r}{b - a}\right) & (a < r < b) \\ 0 & (r \geq b) \end{cases} \quad (9)$$

where

$$V_a = \frac{Q_a}{4\pi\epsilon_o} \left(\frac{1}{a} - \frac{1}{b}\right) \quad (12)$$

and

$$V_b = \frac{Q_a - Q_a}{4\pi\epsilon_o b} = 0 \quad (13)$$

Note that this shield does *not* repel electrons since there is no field outside the outer shell. Neither, however, does it attract them as was the case with the single-conductor configuration discussed previously.

### Unequally and Oppositely Charged Spheres

To shield low-energy electrons ( $\approx 1$  MeV) using the outer sphere, there must be a negative potential on the shell at  $r = b$  with

$$|V_b| > 1 \text{ MV} \quad (14)$$

From equation (5),  $V_b$  negative requires that

$$|Q_a| < |Q_b| \quad (15)$$

where equations (3) to (8) again apply. HZE particles incident upon the outer shell will, because of their positive charge, acquire an additional kinetic energy given by

$$T_b = Ze|V_b| \quad (16)$$

For  $^{56}\text{Fe}$  with  $|V_b| = 1$  MV, for example, equation (16) yields  $T_b = 26$  MeV, which is a negligible addition to the ion kinetic energy, and will be ignored. Thus, to repel a  $^{56}\text{Fe}$  nucleus, with a maximum kinetic energy of 1.4 GeV/nucleon, we require  $V_a \geq 3.02$  GV as before.

### Vacuum Breakdown of Electric Field

As a result of vacuum breakdown, the magnitude of the electric-field intensity at the surface of either shell is limited to a value (ref. 2)

$$E_{\text{max}} = 3 \times 10^7 \text{ V/m} \quad (17)$$

From elementary electrostatics, the electric-field intensity is related to the potential as

$$\vec{E} = -\vec{\nabla}V(r) \quad (18)$$

Near the outer surface of the inner shell, equations (18) and (7) yield

$$\vec{E}_a = -\frac{b}{a} \left( \frac{V_b - V_a}{b - a} \right) \hat{r} \quad (19)$$

where  $\hat{r}$  is the unit radial vector and  $\vec{E}_a$  points radially outward since  $|V_b| < |V_a|$ .

Similarly, near the inner surface of the outer shell, equations (18) and (7) yield

$$\vec{E}_{b,\text{inner}} = \frac{a}{b} \left( \frac{V_b - V_a}{b - a} \right) \hat{r} \quad (20)$$

so that, when equations (19) and (20) are compared,

$$\vec{E}_{b,\text{inner}} = \frac{a^2}{b^2} \vec{E}_a \quad (21)$$

Since  $b > a$ , it is apparent that

$$|\vec{E}_a| > |\vec{E}_{b,\text{inner}}| \quad (22)$$

and that the limiting electric-field intensity is on the outer surface of the inner shell.

On the outer surface of the outer shell, equations (18) and (8) yield

$$\vec{E}_{b,\text{outer}} = \frac{V_b}{b} \hat{r} \quad (23)$$

This intensity points radially inward since  $V_b$  is negative.

For  $|\vec{E}_{b,\text{outer}}| = E_{\text{max}}$ , the minimum value of  $b$  is

$$b_{\text{min}} = \frac{V_b}{E_{\text{max}}} \quad (24)$$

which, for  $V_b = 1$  MV and  $E_{\text{max}} = 3 \times 10^7$  V/m, yields  $b_{\text{min}} = 0.03$  m.

Again on the outer surface of the inner shell, equation (19) can be used to establish the relative sizes of the concentric shells and to specify the minimum-shell radii necessary to prevent vacuum breakdown. If

$$|\vec{E}_a| \leq E_{\text{max}} \quad (25)$$

then equation (19) yields

$$a = \frac{V_a - V_b}{E_{\text{max}}} \left( \frac{1}{1 - \frac{a}{b}} \right) \quad (26)$$

This equation relates the radii to the specified potentials and the vacuum breakdown field intensity. Solutions to equation (26) for  $a$  and  $b$ , where  $V_a = 3.02$  GV,  $V_b = -1$  MV, and  $E_{\text{max}} = 3 \times 10^7$  V/m, are listed in table I. Although the minimum radius of the inner shell is approximately 100 m, the resultant outer shell

is quite large. The minimum radius of the outer shell occurs when  $a = 200$  m. This would probably be the minimum-mass shield if both shells were approximately the same thickness and constructed of the same material. Finally, for  $a = 200$  m and  $b = 400$  m, the required charges on the two spherical shells can be calculated from equations (3) and (5). Clearly, these minimum dimensions suggest that electrostatic shielding is not reasonable for small spacecraft.

### Stability and Other Considerations

As shown in references 1 to 3, any deviation from concentricity creates a redistribution of charge on the surfaces of the spheres, such that a net force of attraction is established between them. Hence, rigid support members are required to maintain sphere separation.

When selecting possible support members, consideration of their voltage breakdown characteristics must be included, because any supporting structure between the two spheres would yield the limiting electric-field intensity rather than the vacuum. Derivations of the net force between nonconcentric spheres are given in references 1 and 2. Finally, apertures for personnel access, attitude control, and propulsion would provide possible sites for breakdown of the generated fields (ref. 3). In addition, there could be a severe shock hazard for any extravehicular activity by the astronauts (ref. 4).

### Summary of Results

To shield against the major galactic heavy ion of radiobiological interest,  $^{56}\text{Fe}$ , while simultaneously shielding against low-energy electrons of the Van Allen belts and/or solar wind, a concentric-sphere shield arrangement is necessary, since these particle types are oppositely charged. For the  $^{56}\text{Fe}$  nuclei, shielding from particles with kinetic energies up to 1.4 GeV/nucleon was arbitrarily chosen for analysis purposes. The potential required to accomplish this was 3.02 GV. For the outer sphere, shielding from electrons with kinetic energies of approximately 1 MeV required a much smaller potential (approximately 1 MV).

The physical dimensions of the concentric sphere arrangement were dictated by considerations of electrical breakdown of the vacuum at an electric-field intensity of  $3 \times 10^7$  V/m. As shown in table I, the minimum allowable inner-shell radius was approximately 100 m if the outer-shell radius was extremely large (on the order of  $10^4$  m or more). The minimum-mass shield arrangement (table I) appears to be one where the inner shell has a radius of 200 m and the outer shell a radius of 400 m.

### Concluding Remarks

The use of electrostatic fields to shield spacecraft

against galactic heavy ions has been analyzed for incident high-energy iron nuclei which are the dominant high-energy heavy-ions (HZE particles) of radiobiological interest. The potential required to repel these ions was found to exceed current state of the art in electrostatic-field generation by approximately 2 orders of magnitude. This requirement essentially eliminates the concept as a viable alternative to bulk-material shielding. In addition, electrical breakdown considerations were shown to limit the minimum physical size of the shield configuration to dimensions on the order of hundreds of meters. This limitation clearly renders the concept infeasible for small exploratory-type spacecraft, even if the lack of an adequate electrostatic-field generation capability were to be overcome in the future.

Langley Research Center  
National Aeronautics and Space Administration  
Hampton, VA 23665  
July 31, 1984

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## Symbols

$a$	radius of inner concentric shell, m
$b$	radius of outer concentric shell, m
$b_{\min}$	minimum radius of outer shell, m
$e$	unit of electronic charge, $1.6 \times 10^{-19}$ C
$\vec{E}$	electric-field intensity vector, V/m
$\vec{E}_a$	electric-field intensity on outer surface of inner shell, V/m
$\vec{E}_{b,\text{inner}}$	electric-field intensity on inner surface of outer shell, V/m
$\vec{E}_{b,\text{outer}}$	electric-field intensity on outer surface of outer shell, V/m
$E_c$	cutoff energy, GeV/nucleon
$E_{\max}$	magnitude of electric-field intensity for vacuum breakdown, $3 \times 10^7$ V/m
$n(> E_c)$	number of nuclei per $\text{cm}^2$ per day having an energy greater than $E_c$
$Q_a$	charge on inner shell, C

$Q_b$	charge on outer shell, C
$r$	arbitrary-position radius vector, m
$\hat{r}$	unit radial vector
$T$	ion total kinetic energy, GeV
$T_b$	defined in equation (16), MeV
$V(r)$	electrostatic potential, V
$V_a$	electrostatic potential on inner shell, V
$V_b$	electrostatic potential on outer shell, V
$Z$	ion charge number
$\vec{\nabla}$	spatial gradient operator, $\text{m}^{-1}$
$\epsilon_o$	permittivity of free space, $8.854 \times 10^{-12}$ farads/meter

### Abbreviations:

HZE	high-energy heavy ion
LET	linear energy transfer
RBE	relative biological effectiveness

Arrows over symbols indicate vectors.

TABLE I. CONCENTRIC SHELL PARAMETERS

$a/b$	$a$ , meters	$b$ , meters
0.000	100.03	$\infty$
.001	100.13	100 130
.010	101	10 100
.100	111	1 111
.400	167	417
.500	200	400
.600	250	417
.990	10 003	10 104

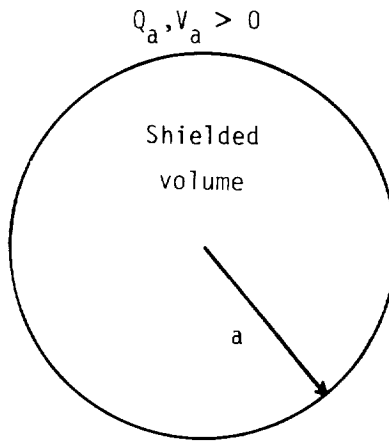


Figure 1. Single, positively charged spherical electrode for shielding from galactic heavy ions.

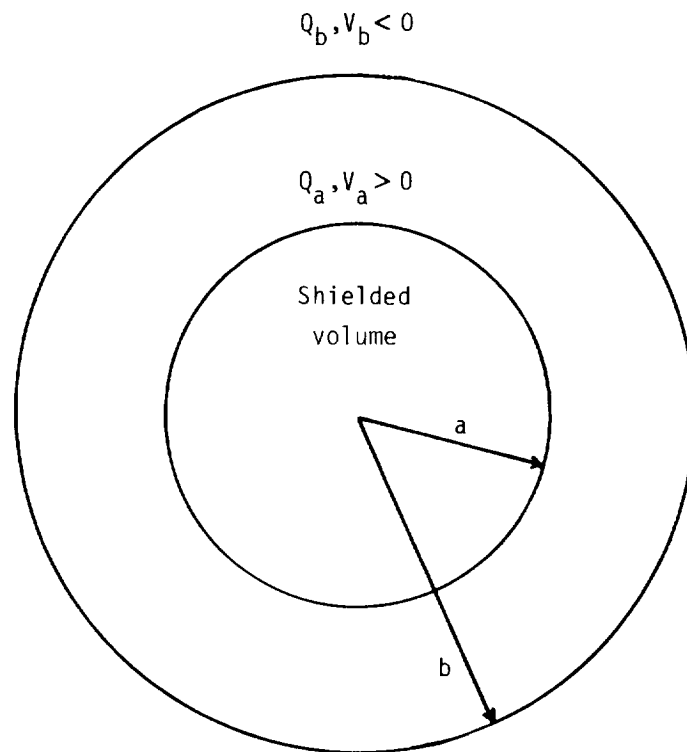


Figure 2. Concentric, oppositely charged spherical electrodes for shielding against galactic heavy ions (inner electrode) and electrons (outer electrode).





1. Report No. NASA TM-86265	2. Government Accession No.	3. Recipient's Catalog No.	
4. Title and Subtitle GALACTIC HEAVY-ION SHIELDING USING ELECTROSTATIC FIELDS		5. Report Date September 1984	
		6. Performing Organization Code 199-20-76-01	
7. Author(s) Lawrence W. Townsend		8. Performing Organization Report No. L-15832	
		10. Work Unit No.	
9. Performing Organization Name and Address NASA Langley Research Center Hampton, VA 23665		11. Contract or Grant No.	
		13. Type of Report and Period Covered Technical Memorandum	
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, DC 20546		14. Sponsoring Agency Code	
15. Supplementary Notes			
16. Abstract The shielding of spacecraft against galactic heavy ions, particularly high-energy $^{56}\text{Fe}$ nuclei, by electrostatic fields is analyzed for an arrangement of spherical concentric shells. Vacuum breakdown considerations are found to limit the minimum radii of the spheres to over 100 m. This limitation makes it impractical to use the fields for shielding small spacecraft. The voltages necessary to repel these $^{56}\text{Fe}$ nuclei exceed present electrostatic generating capabilities by over 2 orders of magnitude and render the concept useless as an alternative to traditional bulk-material shielding methods.			
17. Key Words (Suggested by Authors(s)) Galactic heavy ions Spacecraft shielding Electrostatic shielding		18. Distribution Statement Unclassified—Unlimited  Subject Category 18	
19. Security Classif.(of report) Unclassified	20. Security Classif.(of this page) Unclassified	21. No. of Pages 8	22. Price A02



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Space Administration

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